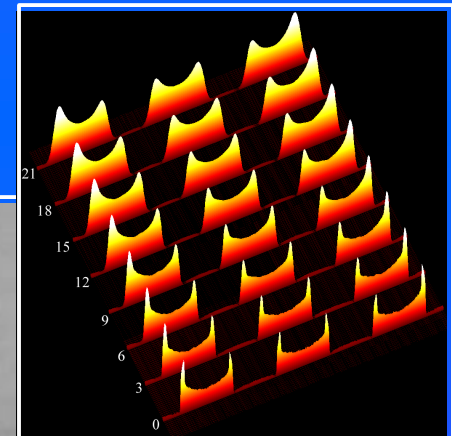
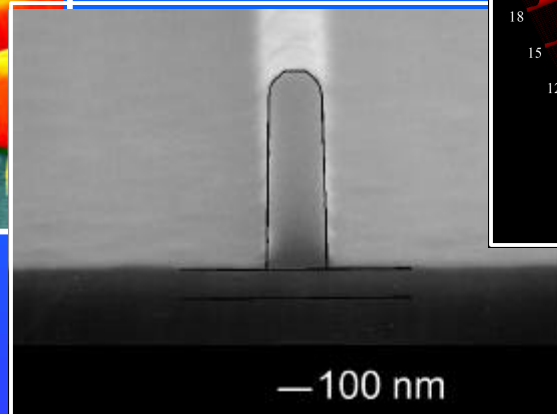
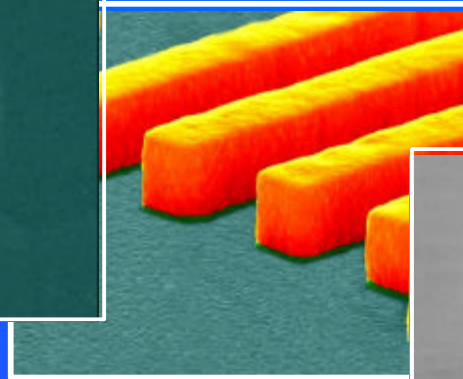
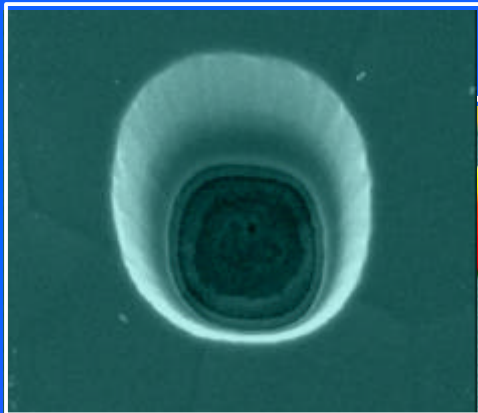


# Nanometer-Scale Metrology

Michael T. Postek, Program Manager



# Nanometer-Scale Metrology

## Goal

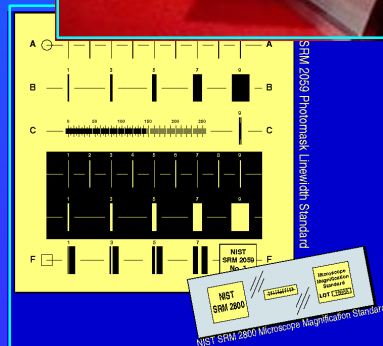
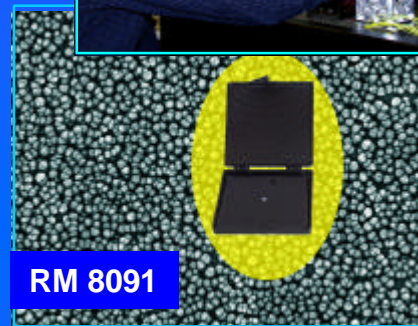
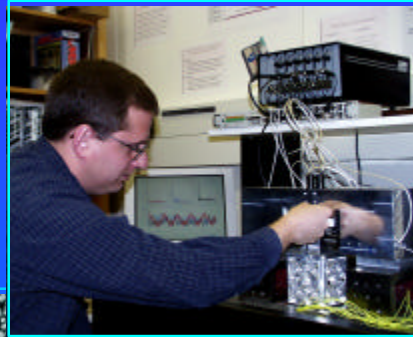
- To enable the microelectronics industry to sustain and improve its multibillion-dollar production, through their adoption of NIST traceable length standards and infrastructural metrology methodologies for nanometer to meter scale lengths sufficient to support the industry's production goal of 100 nm devices by 2005.

## Deliverables

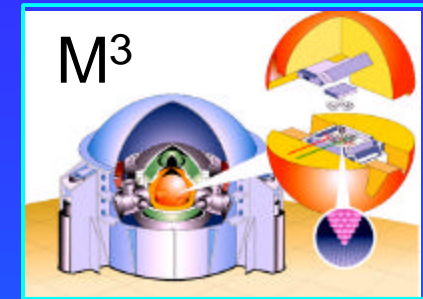
- Issue RM 8091, SRM 2800
- Issue RM 8090/SRM 2090
- Advanced, shape sensitive measuring methods for the microelectronics industry
- Provide "Best-in-the-World Linescale Measurements"

## Customers and Collaborators

- ISMT, OMP, NASA, ANL, MIT, UNCC
- Schlumberger ATE, Dow Chemical,
- IBM, Photronics, Intel, AMD, KLA, Tencor, SPECTEL, Sterling Semiconductor,
- ADC Telecommunications, Compugraphics

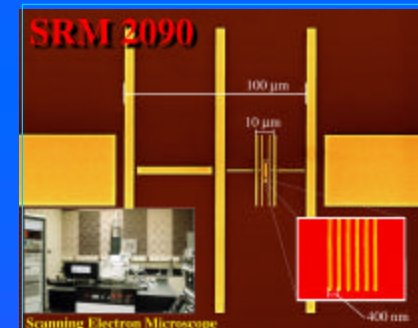


## Research



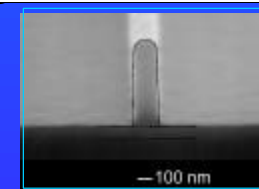
- 10 nm accuracy two-dimensional feature placement measurements over a 50mm by 50 mm area with sub-nanometer feature and measurement resolution

## Development



- SRM development for instrument magnification and width calibration

## Modeling and Simulation



- Advanced shape sensitive measurement methods and simulations

# NSM Program Relevance

## ITRS Requirements

Working to find solutions

NEED

Technology Node	180 nm	130 nm	100 nm	70nm	50nm	35nm	Driver
<b>Lithography Metrology</b>							
Wafer Gate CD nm post-etch control	2.4	8	6	5	3	2	MPU
Wafer CD Tool 3 $\sigma$ Precision P/T=0.2 Isolated Lines	2.4	1.6	1.2	1	0.6	0.4	MPU
Overlay Control (nm) (mean +3 $\sigma$ )	65	45	35	25	20	14	MPU
Overlay Metrology Precision (nm) P/T=0.1	6.5	4.5	3.5	2.5	2	1.4	MPU
<b>Front End Processes Metrology</b>							
Logic Dielectric Thick Precision 3 $\sigma$ (nm)	0.0075	0.006	0.004	0.0032	0.0024	0.002	MPU
Metrology for Ultra-Shallow Junctions at Channel Xj (nm)	50.4	32.4	23.6	16.4	11.6	8	MPU
<b>Interconnect Metrology</b>							
Barrier layer thick (nm) process range ( $\pm 3\sigma$ ) Precision 1 $\sigma$ (nm)	23 20% 0.08	13 20% 0.04	3 20% 0.01	X	X	X	MPU
<b>Defect Reduction</b>							
<b>Patterned Wafer Inspection, PSL Spheres at 90% Capture, Equivalent Sensitivity (nm)</b>							
Yield ramp at 3,000 (cm <sup>2</sup> /hour)	72	52	40	28	20	14	0.4xDR
<b>High Aspect Ratio Feature Inspection: Equivalent Sensitivity in PSL Diameter (nm) at 90% Capture Rate.</b>							
All stages of manufacturing	54	39	30	21	15	11	0.3xDR

3D CD-SEM, Scatterometry, CD-AFM...

Overlay Project

Thermawave Optiprobe

Boxer-Cross

Philips Anal Impulse 300

Advanced Defect Inspection

Metrology solutions at the nanoscale for the Microelectronics Industry applies to many other industries

# Atomic Displacement Metrology

Project Leader: Thomas LeBrun

## 2001 Deliverables

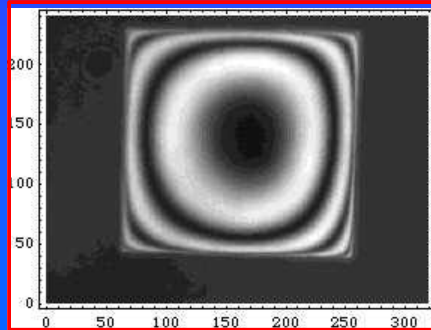
- Complete the necessary research and develop a vacuum chamber and fine stage to compensate for errors for the Atomic Displacement Metrology (ADM) testbed including a control system for the 6 DOF stage and to install an x-ray interferometer in the 50 mm test bed chamber.

## Customers and Collaborators

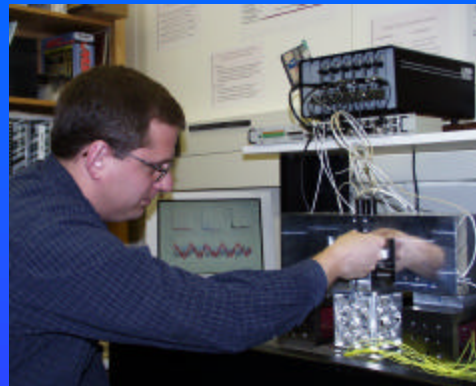
Stuart Smith, Rich Seugling,  
Precision Engineering Center,  
University of North Carolina at  
Charlotte

Tim Thompson, Steve Ney, Eric  
Ponslett, Hytec Inc., Los  
Alamos NM

David Trumper, MIT



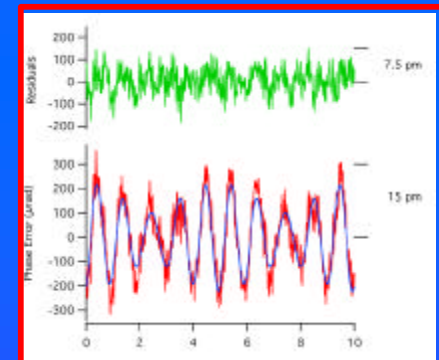
X-ray interferometer is tested to ensure flatness.



Testing the six-degree-of-freedom fine stage and the phasemeter array.

## FY 2000 Accomplishments

- Vacuum Isolation system delivered and under construction.
- XRI alignment system built and ready for test.
- Phasemeter array attains 15 pm errors.



- Six-degree-of-freedom Fine stage delivered and tested.
- Next Generation LSI being built next to current LSI.

# Integrated Dimensional and Electrical Metrology of Nanostructures

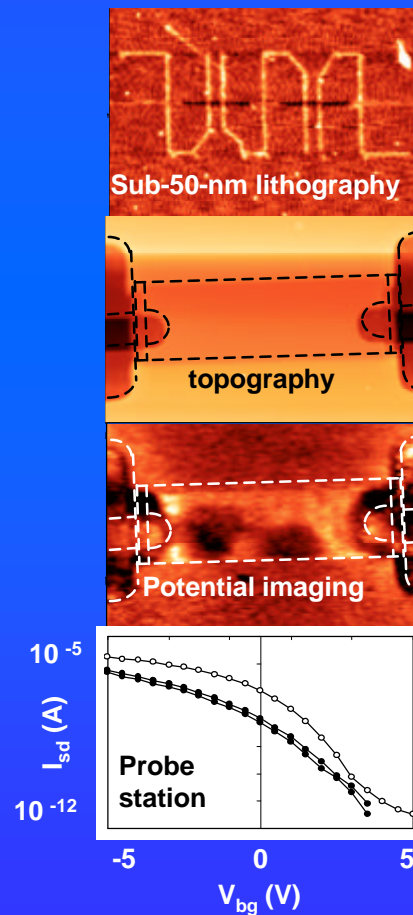
Project Leader: John Dagata

## 2001 Deliverables

- Develop the instrumentation and techniques necessary to integrate simultaneous dimensional and electrical measurements using local-probe techniques
- Present a paper at the SPIE Microlithography meeting on the methodology

## Customers and Collaborators

- University of North Carolina, Chapel Hill
- Electrotechnical Laboratory (ETL), Japan,
- Universitat Autònoma de Barcelona, Spain
- Matsushita Electrical, Japan.



## FY 2000 Accomplishments

- Constructed integrated probe station and scanned probe microscope
- Designed and fabricated test device: silicon-on-insulator field-effect transistor
- Initial test results illustrated at left



# Length Scale Interferometer Development and Line Scale Measurement Calibration Services

**Project Leader: William Penzes**

## 2001 Deliverables

- Provide traceable calibration of graduated length scales, grid plates and long gage blocks (END Standards) for internal, U.S. and International customers.
- Update the control software of the Line Scale Interferometer (LSI) to continue to deliver accurate "Best-in-the-World" length measurements

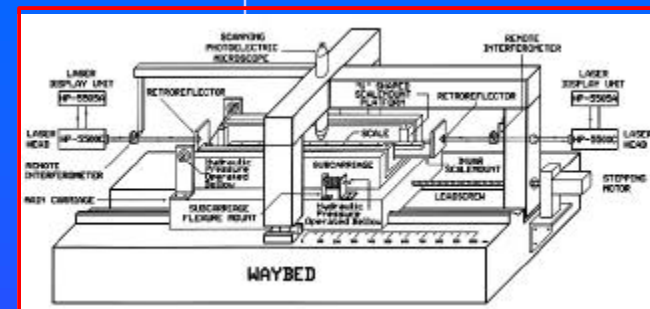
## Customers and Collaborators

AMP Inc., Cubic Precision, Bausch & Lomb, Lockheed Martin Astronautics, Mitutoyo Co., Fryer Co. Inc., Whitehouse Scientific Ltd., First Energy Co., AK Steel Co., David L. Ellis Co. Inc., M&R Optical, B&W Services, TRW Space & Defense, Boeing Commercial Airplane Co., Max Levy Autograph, Compugraphics, Inc.



## FY 2000 Accomplishments

- Provided technical information for 47 customers.
- Completed the BIPM #12924 meter bar measurements.
- The SN3701 900 mm long gage block measurement was completed for the CLL-K2 round robin project.
- Provided high accuracy calibrations for 18 customers.

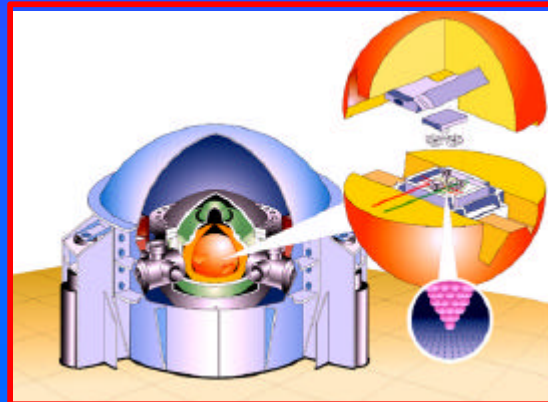


- The LSI Super Invar microscope support components machine work was finished.
- The LSI data acquisition and control software was modified.

# Molecular Measuring Machine Research and Development Project Leader: John Kramar

## 2001 Deliverables

- Complete a fully operational and user-interfaced instrument capable of 10 nm accuracy two-dimensional feature placement measurements over a 50mm by 50 mm measurement area, and having sub-nanometer feature and measurement resolution.



## FY 2001 Plans

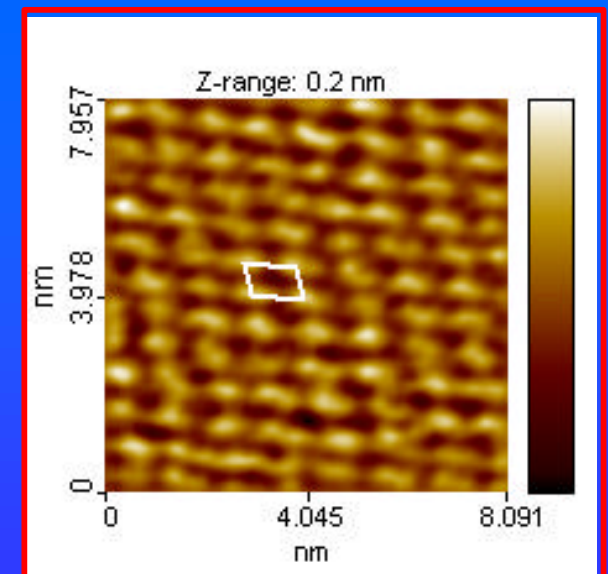
- Validate the scale and geometry of M3 measurements against a known crystal lattice.
- Restore operation of the temperature control system.
- Validate long-distance pitch measurements using LFAD Cr gratings.
- Measure customer gratings.

## Customers and Collaborators

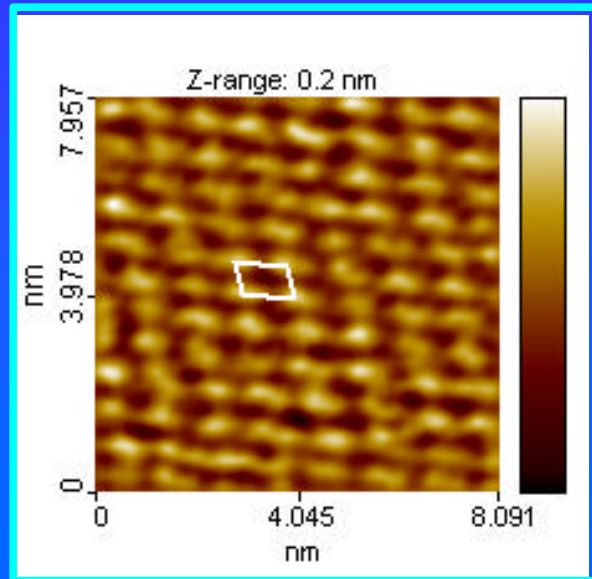
- NASA
- Argonne National Laboratory

## FY 2000 Accomplishments

- Reassembled M<sup>3</sup> with redesigned components.
- Demonstrated lattice-resolved imaging under closed-loop control.
- Improved user interface and control algorithms.



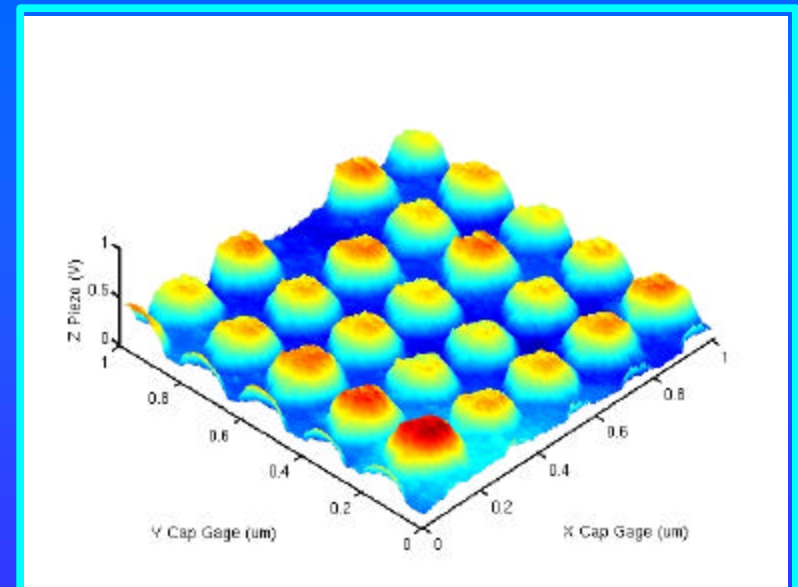
# M<sup>3</sup> Achieves Lattice Resolution Images



## FY 2000

- Reassembled M<sup>3</sup> and got first image. (last Assessment Panel visit)
- Shake-down and adjustment of sensor gain, noise sources, control parameters, and interferometers.

- First lattice-resolution images and measurements of an organic electrically conductive crystal (TEET)[Ni(dmit)<sub>2</sub>]<sub>2</sub>
- Lattice Spacing for the basal plane 1.02 nm and a 1.67 nm step height.
- Provides a comparison of M<sup>3</sup> functionality against a known crystal lattice
- Collaboration with Argonne National Laboratory





# Optical Standards for Integrated Circuit Dimensional Metrology

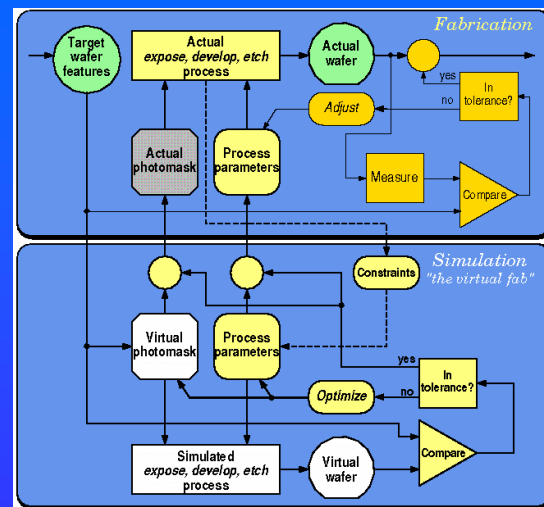
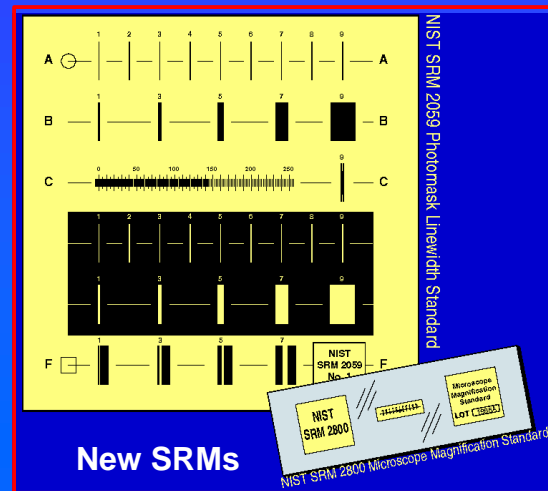
## Project Leader: James Potzick

### 2001 Deliverables

- Complete the calibrations and documentation necessary for the issuance of Standard Reference Material SRM 2800 (a new NIST traceable scale micrometer).
- Complete the calibrations and documentation necessary for the issuance of Standard Reference Material SRM 2059 the new photomask linewidth standard

### Customers and Collaborators

International SEMATECH  
Office of Microelectronics  
Programs  
The Neolithography Group  
BIPM



Process modeling  
for improved metrology

### FY 2000 Accomplishments

- The NIST UV Scanning Microscope modified, improved, and in production, calibrating SRM 2800.
- Library of modeled photomask line images being developed.
- SEMI Standards task force document Terminology for Microlithography Metrology has become SEMI Standard P35.
- Invited paper Photomask metrology and neolithography presented at Advanced Reticle Symposium in San Jose, Calif.
- Neolithography Group coordination transferred to International SEMATECH

# Atom-based Artifacts and Atomic Imaging Tool Development

Project Leader: Richard Silver

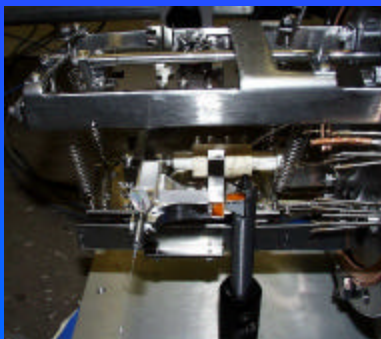
## 2001 Deliverables

- Develop the methods to prepare photolithographically patterned three-dimensional structures in silicon adequate for atom-based dimensional metrology in collaboration with SEMATECH.

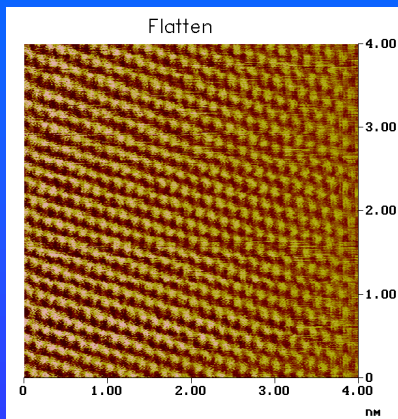
- Develop the methods for preparation of surfaces with long range atomic order in silicon and improve wet chemistry surface preparation methods for use in dimensional measurements on the atomic scale.

## Customers and Collaborators

- International SEMATECH
- Office Of Microelectronics Programs



Measurements of atoms on semiconductor surfaces



First UHV-STM/Interferometer Graphite Data

## FY 2000 Accomplishments

- Obtained routine reconstruction of Si (111) surfaces with long range atomic order at high temperatures.

- Developed wet Si processing methods to lower atomic reconstruction temperatures on Si etched structures.

- Correlate atomic resolution imaging of FIFEM tips with atomically resolved artifacts. Develop and publish new model of atomic dimension tip shapes.

- Fabricated new linewidth photomask and have wafers fabricated at SEMATECH specifically for linewidth metrology and atom counting.

- Designed the hardware and installed the components on the UHV-STM to enable the first direct measurements with interferometry of lateral atomic spacings.

- Completed the assembly of the vacuum suitcase UHV segments and demonstrated UHV transportation of GaAs atom-based metrology sample from Bldg 220 to Bldg 225.

# Optical Overlay Metrology Research and Optical Overlay Metrology Standards Development

Project Leader: Richard Silver

## FY 2000 Accomplishments

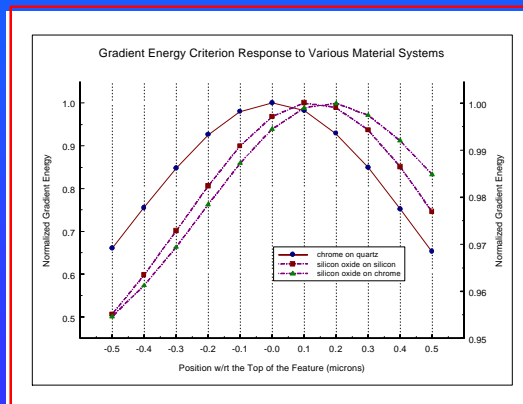
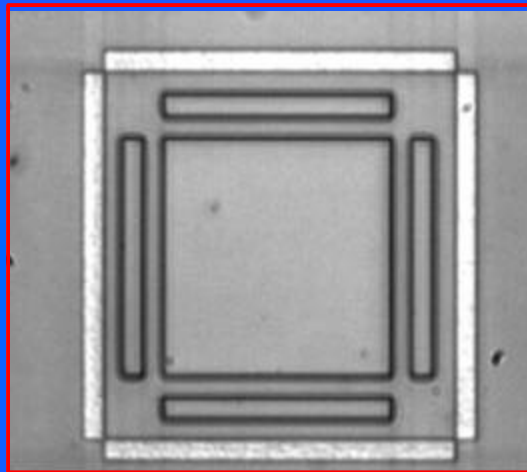
- Developed overlay target reticles and fabricated comprehensive prototype wafer standards at SEMATECH
- Developed and analyzed automatic focus algorithms including a new frequency-based method
- Used cross-correlation and recently developed edge detection methods to improve edge position repeatability and accuracy
- Used the SPECTEL Metrologia model to analyze the overlay data and significantly improved the analysis
- Designed and fabricated the microgrid for CCD calibration and optical system calibration.

## 2001 Deliverables

- Complete the design of new reticles for overlay metrology and have new wafers fabricated for overlay standards based on a comprehensive evaluation of the prototype set of overlay artifact test standards
- Complete the formal qualification process of the microscope optics and the x-y metrology, investigate the key issues in overlay metrology and develop comprehensive modeling capabilities for centerline and edge detection methods.

## Customers and Collaborators

- International SEMATECH, IBM, AMD, Intel, Motorola, KLA-Tencor, Schlumberger
- Office of Microelectronics Programs



# ISMT Collaboration for the Development of Overlay Wafer Standards and Test Structures

- A two-level reticle set was fabricated with a comprehensive set of overlay patterns and test structures. The wafers are being measured at several fabs for evaluation in a production environment.



- There are extensive overlay targets, characterization arrays and CD features. Process levels are double-etched Si structures, contact to poly and photoresist.
- NIST is working closely with several industrial experts for the development of new CCD array, optical system and data analysis methods.

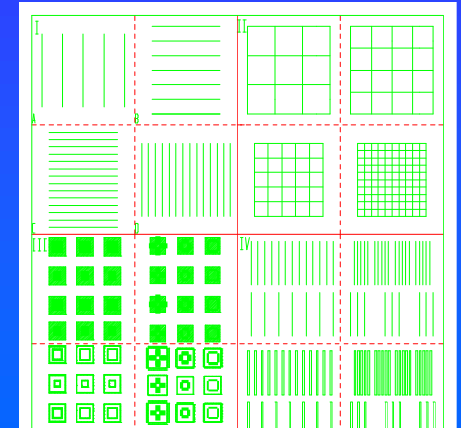
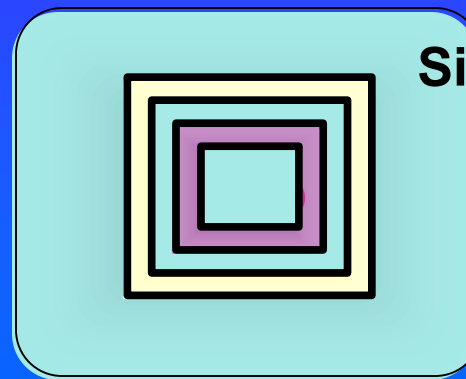
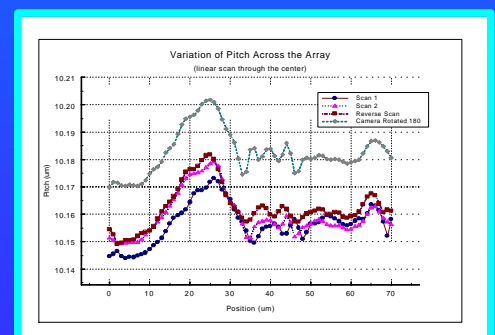
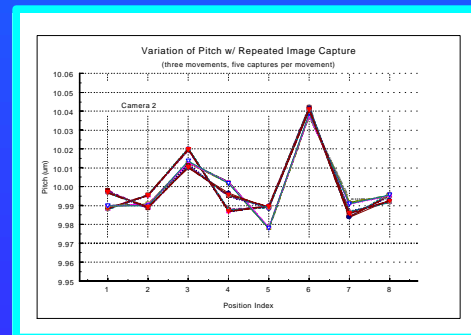
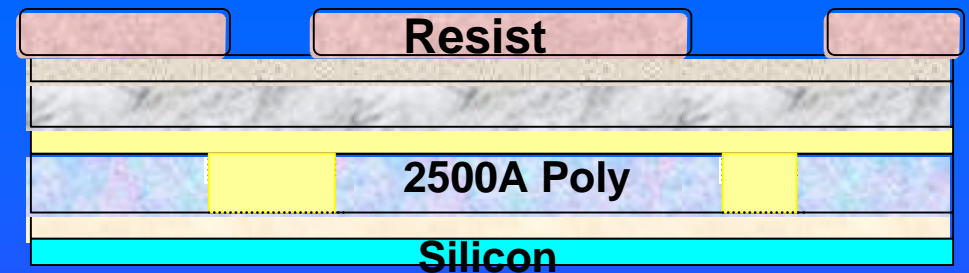


Figure 1



# Model-Based Linewidth Metrology Project

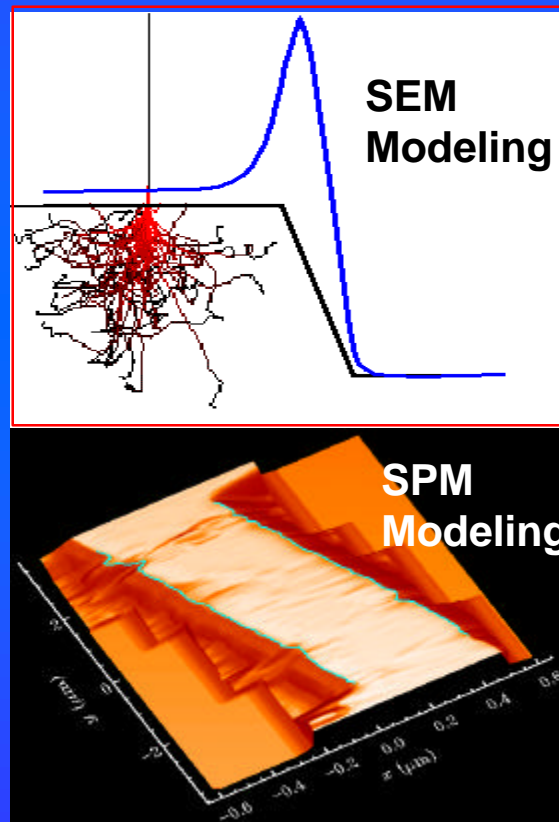
## Project Leader: John Villarrubia

### 2001 Deliverables

- Design and implement a provisional model-based shape-sensitive linewidth measurement system for an industrially relevant sub-500 nm sample, complete the SEMATECH contract on Polysilicon linewidths, and present a paper on this topic at the SPIE Microlithography meeting.

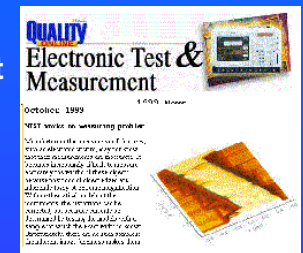
### Customers and Collaborators

International SEMATECH  
Office of Microelectronics  
Programs  
BFRL  
Dow Chemical



### FY 2000 Accomplishments

- Completed comparison of SEM and electrical linewidths on BESOI
- Publications: 5 on Linewidth measurement, SEM modeling, and SPM modeling.\*
- Oral Presentations: 6 (5 invited) to companies, industry consortia and conferences.
- Commercialization: Applied Probes and Image Metrology, announced products based upon our SPM modeling
- Publicity: Project results featured as “Industry News” in *Quality Magazine*.



\*3 additional “spin-off” publications: Our methods are now being used in Nanoindentation measurements



# SEM Linewidth, Magnification and Sharpness Metrology

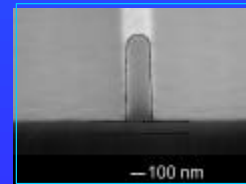
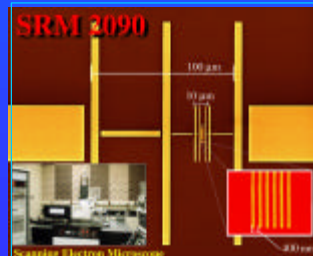
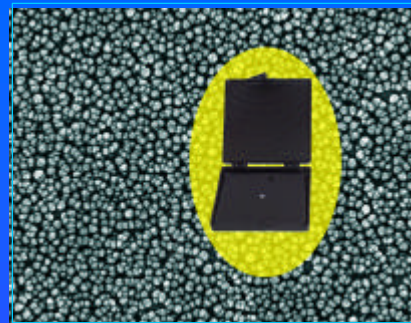
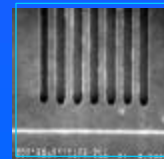
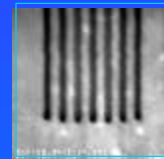
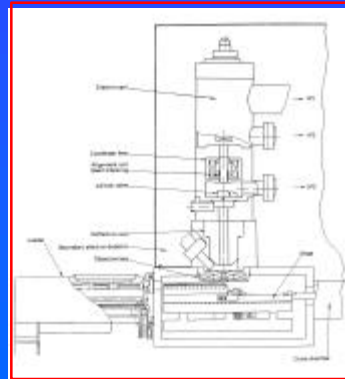
## Project Leader: Andras Vladar

### 2001 Deliverable

- Development of standard artifacts relevant to the microelectronics industry
- Development of accurate and precise SEM metrology
- RM 8091 Sharpness Reference Artifact
- Nano-tip electron gun experiments
- Advanced, shape sensitive measuring methods for the microelectronics industry

### Customers and Collaborators

- US microelectronics industry
- International SEMATECH
- Office of Microelectronics Programs
- Schlumberger ATE, SPECTEL, XEI, Hitachi, Applied Materials



### FY 2000 Accomplishments

#### SYSTEM DEVELOPMENT

- SEM Sentinel
  - Performance measuring system
- Nano-tip SEM
  - Underway, promising results
- Improvements
  - S-4700 upgrade;
  - E-beam lithography system
  - High-resolution PC imaging

#### REFERENCE ARTIFACTS

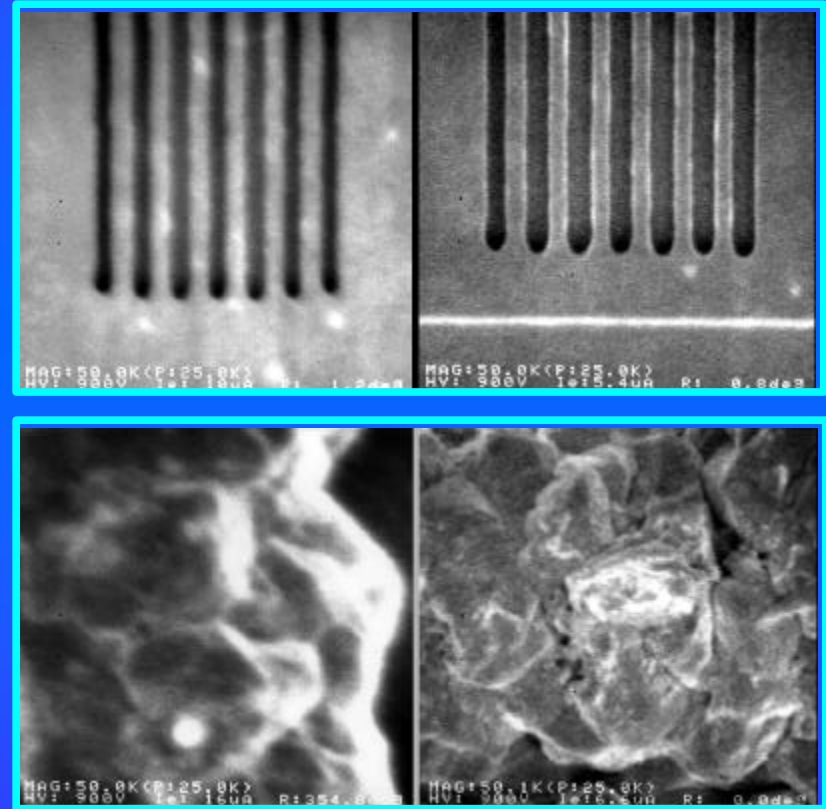
- RM 8091 Sharpness
  - Soon to be released
- RM 8090 Pitch
  - In production, new design

#### METHOD DEVELOPMENT

- Model-based metrology
  - Accurate, shape-sensitive
  - Production polySi wafer samples

# ISMT Collaboration in the Development of Nano-tips to Enhance the Performance of Production CD-SEMs

- The use of atomically sharp nano-tips are theorized to increase the performance of CD-SEMs and thus extend their usefulness via the ITRS roadmap.
  - Improved resolution
  - Improved brightness
- NIST is testing the concept first with “sharp-tips” (FY00) and then nano-tips (FY 01) fabricated at UT (Joy) and NIST (Silver) on the CD-SEM donated by Texas Instruments.
- Highly successful first year of the contract proved that performance improves even with the installation of sharp-tips.

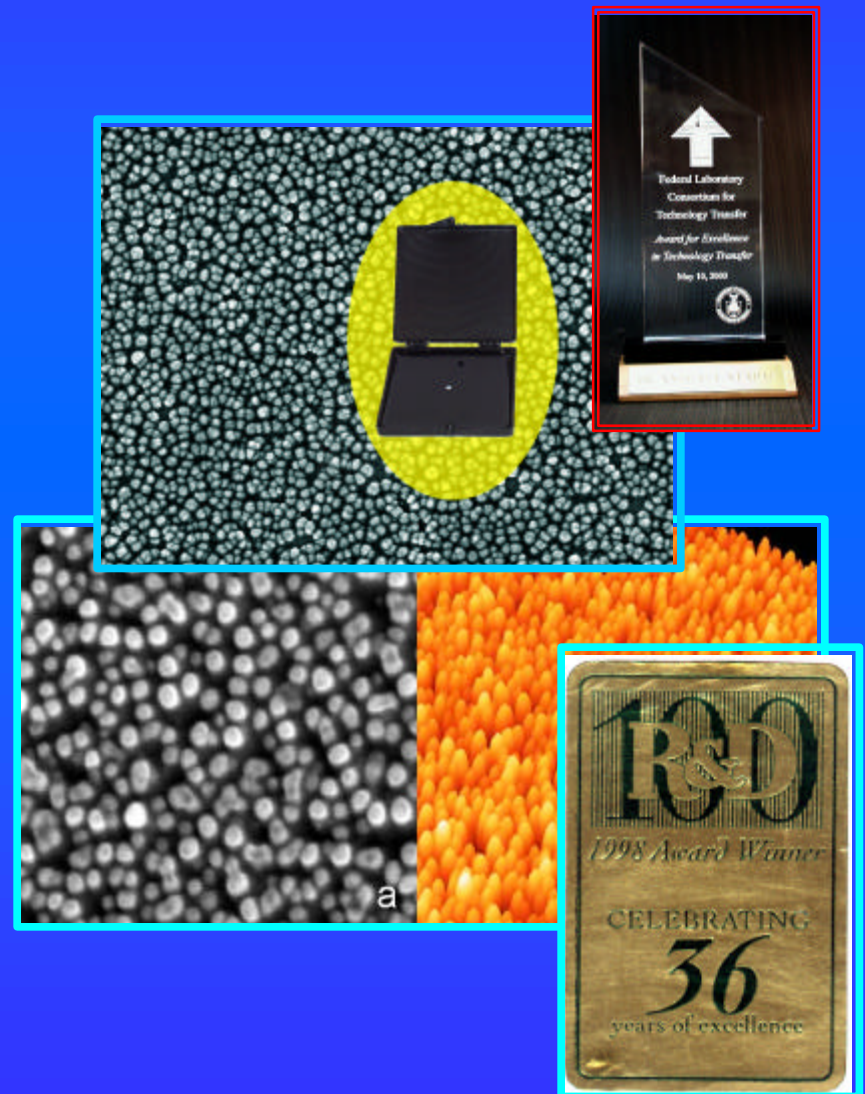


CD-SEM Performance improvement demonstrated with sharp tips.

# Reference Material (RM)8091

## Next Step in the SEM Sharpness Analysis

- Release of RM 8091 to be announced at SPIE Microlithography 2001
- 15 samples to be presented to ISMT for distribution to the member companies at the ISMT Metrology Meeting.
- Released as a small diced chip.
- A limited number of drop-in wafers are available through OSRM.
- For use with the Spectel SEM Monitor Program, NIST Kurtosis Program or the UT SMART Program.
- SEM Monitor was Awarded a Y2000 Federal Laboratory Consortium award for Excellence in Technology Transfer and a 1998 R&D 100



# Nanometer-Scale Metrology

## Highlights

- 39 technical outputs
- 18 presentations
- 2 Tutorials
- 2 Short Courses
- 4 Workshops
- 2 FY00 ISMT Contracts Completed
- 2 New International SEMATECH (ISMT) contracts impending
- ISMT Final Report on Part I Nano-tip application completed early
- ISMT Final Report on Polysilicon LW sample completed early
- SPIE Microlithography Overall Symposium Chair - Postek
- Award of a Research Fellowship by Japan's Science and Technology Agency - Dagata
- Dissertation- Fox, S. 2000. Focus, Edge Detection, and CCD Camera Characterization for Development of an Optical Overlay Calibration Standard, (R. Silver Thesis Advisor), Graduate Thesis, Univ. of MD, 2000.

# Nanometer-Scale Metrology

## Selected Key 2000 Publications

- Perez-Murano, F., K. Birkelund, K. Morimoto, J. A. Dagata, Voltage modulation scanned probe oxidation, Appl. Phys. Lett. 75 199 (1999).
- Potzick, J. 1999. Noise averaging and measurement resolution (or a "little noise is a good thing"). Review of Scientific Instruments Vol 70(4): 2038-2040.
- Kramar, J.A.; Jun, J.S.; Penzes, W.B.; Scire, F.E.; Teague, E.C.; Villarrubia, J.S. Molecular Measuring Machine Design and Measurements. Proceedings of the 1st EUSPEN Topical Conference on Fabrication and Metrology in Nanotechnology, Copenhagen, Denmark, May 28-30, 2000 pp. 34-44. technology. (1999 Version). **INVITED KEYNOTE PRESENTATION**
- Penzes, W. B., Allen, R. A. Cresswell, M. W., Linholm, L. W. and Teague, E. C., 1999. A new method to measure the distance between graduation lines on graduated scales. IEEE Transactions on Instrumentation and Measurement 48(6).



# Nanometer-Scale Metrology

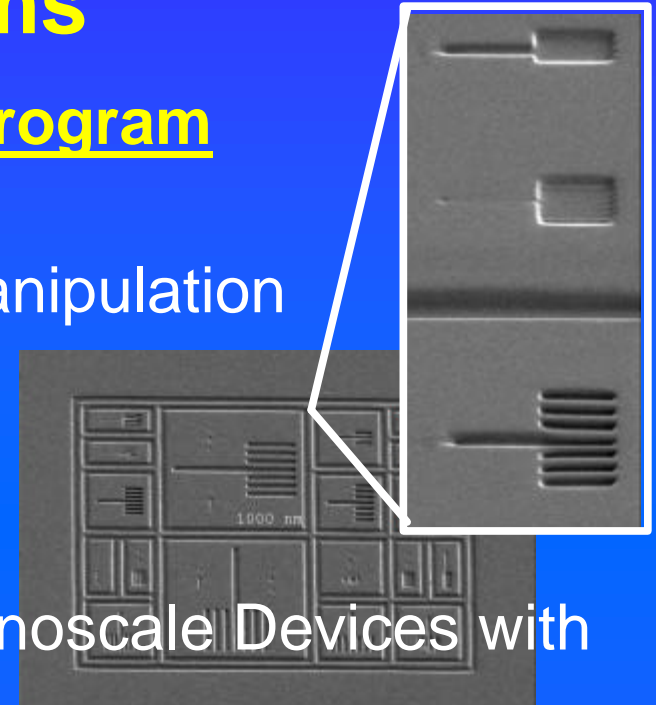
## Selected Key 2000 Publications

- Deleporte, A. G., Allgair, J., Archie, C., Banke, G. W., Postek, M. T., Schlesinger, J., Vladár, A. E., Yanof, A. 2000. Benchmarking of Advanced CD-SEM's against the New Unified Specification for sub-0.18 Micrometer Lithography. SPIE 3998:12-27. and **SEMATECH Tech.Transfer Document.**
- Dongmo, L. S., Villarrubia, J. S., Jones, S. N., Renegar, T. B., Postek, M. T. and J. F. Song. 2000. Experimental Test of Blind Tip Reconstruction for Scanning Probe Microscopy. Ultramicroscopy 85(3):141-153.
- Zhang, N-F, Postek, M. T., and R. D. Larrabee. 1999. Image sharpness measurement in scanning electron microscopy. Part 3. Kurtosis. SCANNING 21:256-252.

# Nanometer-Scale Metrology Allied Programs

## MEL Nanomanufacturing Strategic Program

- Lead on three projects
  - Atom-Scale Measurement and Manipulation
    - Richard Silver
  - Nanolithography of Devices
    - Tom LeBrun
  - Manipulation and Assembly of Nanoscale Devices with Optical Tweezers
    - Tom LeBrun



## High-Accuracy Two-Dimensional Measurements

- Engineering Metrology

## Micro-force Competence – MMD

## NSM has cross-collaborations with every NIST laboratory

# **International Standards Activities**

## **Support of the BIPM MRA**

- **CIPM Key Comparison CCL-K2**
  - Calibration of Long Gauge Blocks
- **CIPM Key Comparison WGDM-7**
  - Nano-3: Linescales
- **CIPM Key Comparison WGDM-7**
  - Nano-1 Linewidth Standards
    - Pilot Laboratory
    - SRM 475

**“The metrological equivalence of national measurement standards will be determined by a set of key comparisons....”**

**“The goal... is to demonstrate the equivalence of routine calibration services offered by NMI's to clients, as listed in Appendix C of the Mutual Recognition Agreement (MRA) [BIPM, 1999]**

# NSM Resources

- Funding – approximately \$3.2-3.3 M
  - About \$2.61 M devoted to salaries (and ~\$200 K devoted to MELSA)
- Personnel - 11 FTE technical staff + secretary + 10 Guest Researchers
  - Loss of Lowell Howard – Industry Position
  - Loss of Fred Scire – Retirement (Guest Researcher Contract)
  - Loss of Steven Fox – Post Doc - Industry Position
  - Gain – Vincent Scheuerman
  - Gain – Satoshi Gonda – NRLM Guest Researcher
  - Gain – Forest Chen – Taiwan
  - Gain – Yann Bednarek - France
- Needed Resources
  - Technicians
    - SEM Metrology
    - M3/Atom-based
    - New LSI development
  - Equipment
    - METROLOGY CD-SEM – SEMATECH Collaboration on RMS